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Environmental thermal influence over soundscape perception: a test room experimental campaign involving the psychological and physiological description of the indoor environment

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Environmental thermal influence over soundscape perception: a test room experimental campaign involving the psychological and physiological description of the indoor environment

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Abstract. Human environmental perception leads occupants' behaviour when interacting with buildings components, affecting the final building energy performance. A solid understanding of human comfort perception includes simultaneous multisensory stimuli and cross-modal interactions among different comfort domains. This study aims to explore the cross-modal effect between thermal and acoustic domains. Each of the 40 subjects took part in a multisensory survey under two different stationary environmental temperature settings. Results show that people in thermally warm conditions are less confident in describing the provided acoustic records. To perform the same procedure but providing a decreasing air temperature ramp would lead to a better interpretation of the results of this campaign.

1. Introduction

Occupants' behaviour significantly impacts building energy performance [1], [2]. It strongly relates to their environmental perception [3], which can be defined as 'human comfort' when a cognitive process elaborates several environmental multisensory stimuli collected by the body with a positive psychological response. Even if the scientific community has recently been pushing to understand the cross-modal interactions among different spheres of comfort [4], [5], the current standards and design guidelines still focus on a single environmental factor at a time [6]–[9]. A deeper understanding of the mechanism beyond human comfort perceptions and domains is thus needed to quantify existing interactions among different comfort spheres, also according to different indoor-outdoor contexts [10].

During the last decades, some studies specifically focused on the combined effect of thermal and acoustic comfort spheres on subjects' cognitive performance and overall comfort perception to provide guidelines for a better design of air-conditioning and ventilation systems in workplaces [11]–[15]. Alm et al. [11] observed that a 1 °C change in operative temperature impacts the overall perception as a 3.8 dB(A) change in sound pressure level. Pellerin and Candas pointed out a decrease in acoustic sensation under thermal conditions far from neutrality and a worsening in thermal perception due to a rise in noise level [12], [16].

Other studies pointed out the role of not-acoustic environmental factors on soundscapes evaluation [17]–[20]. Jin et al. [21] focused on the effect of sound types and sound levels on acoustic, thermal, and overall comfort in a laboratory experiment simulating outdoor thermal conditions typical of different seasons. Results showed that a range of sound affected thermal comfort under different thermal boundary conditions in multiple ways. Nevertheless, the impact of the thermal environment on soundscapes evaluation still needs to be investigated. The present study aims to stress this point through a laboratory experiment specifically designed to assess changes in soundscapes evaluation under two different thermally-stationary conditions moving from neutrality towards a warmer environment.

2. Materials and methods

The main investigation approaches of human-related research studies can be broadly categorised into (i) in-field and (ii) laboratory experiments. The latter allows researchers to better control the environmental boundaries for examining the impact of specifically designed changes in one single parameter at a time while monitoring preferred human responses (including also physiological signals through wearable devices [22], [23]). For this reason, the experimental laboratory method was the most suitable for this study. A within-subjects experimental campaign has been designed and carried out from October 2020 to January 2021. A total of 40 subjects took part in the experiment, 19 males and 21 females. The sample age ranges between 22 and 33 years old (average ± standard deviation = 27.7 ± 2.4). The following subsections present in detail the adopted laboratory equipment and the experimental protocol.

2.1. The laboratory facility and monitoring set-up

NEXT.ROOM is a laboratory facility specifically designed to perform multi-domain human comfort studies. The facility (4x4x2.7 m) is located inside the laboratories of the Engineering Campus of the University of Perugia (Italy, Cfa Köppen-Geiger climate class [24]).

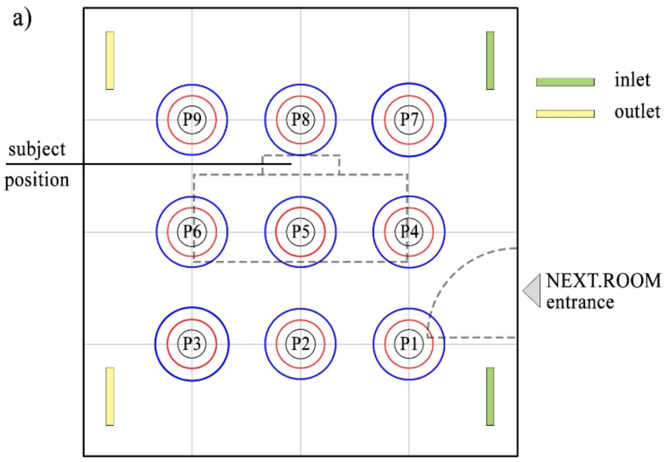
The test room indoor conditions are thermally controlled through both an air conditioning and a radiant system. During the presented experimental campaign, all the surfaces were conditioned at the same temperature to provide a homogeneous thermal environment. The NEXT.ROOM lighting system comprises four LED panels presenting constant luminous flux (3200 lm) and Correlated Color Temperature (4000 K). These were the only light-sources during the present experimental campaign.

According to the standards [25], internal conditions are continuously monitored for assessing thermal, visual, and air quality status. The permanent monitoring set-up is made by all the devices listed in Table 1. No specific audio systems are currently installed in the NEXT.ROOM and the acoustic stimuli are provided through wired noise-cancelling headphones (model WH-1000XM4, by Sony) during the presented experimental campaign.

Table 1. NEXT.ROOM environmental monitoring equipment details.

Monitored parameter	**Sensor accuracy**	**Height**
Air temperature	±0.2 °C	at 1.10 m
Relative Humidity	±1.5 %	at 0.90 m
Globe temperature	±0.2 °C	at 1.10 m
Air velocity	±0.2 m/s	at 0.90 m
CO_2 concentration	< ±50 ppm +2 %	at 0.90 m
Illuminance	±3.0 %	on the desk surface

In order to capture the background noise contributed by different fan speed settings of the mechanical ventilation (MV) system, the internal background noise level was mapped through a sound level meter (model SOLO SLM, by 10db) on a 9-points grid at 1.10 m height (which corresponds to the average height of a sitting person auditory system). The acoustic measurements were carried out under five different internal conditions (MV off, and MV operating at the four available levels of inlet flow). Figure 1 shows the measured background noise with MV off (off in Figure 1b) and with MV operating at the second and fourth levels of inlet flow, the two configurations involved in the experiment (as better presented in the following sub-section). Overall, as expected, the sound level of internal background noise increases directly with the MV's intensity. Sound pressure level (SPL) peaks are highlighted at a low-frequency range (below 500Hz).



b)

Grid point	Ventilation speed level [db(A)]		
	Off	L2	L4
P1	23.7	39.8	58.6
P2	24.3	39.7	57.9
P3	23.3	40.4	60.2
P4	22.8	39.9	59.0
P5	23.1	40.3	58.1
P6	23.9	40.1	58.2
P7	23.7	40.0	60.1
P8	23.1	39.3	58.1
P9	22.9	39.7	57.8

Figure 1. NEXT.ROOM background noise level analysis considering the MV system off, and operating at second (L2) and fourth (L4) levels of inlet flow. Sound level meter was placed at 1.1m of height in each measurement point.

2.2. *The experimental protocol*
The experiment design consists of three main phases and a preliminary part devoted to subject adaptation to the indoor environmental conditions and the experimental procedure explanation (Figure 2).

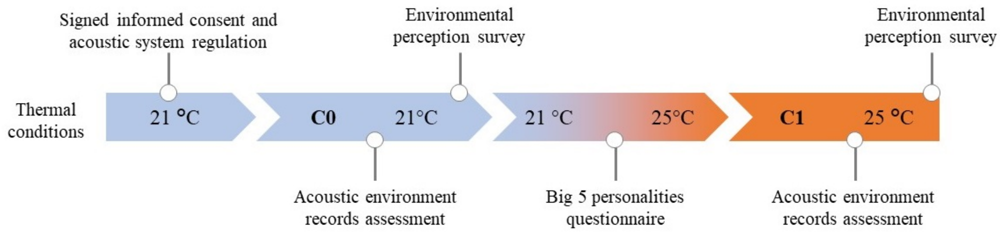


Figure 2. Schema of the experimental test procedure

Throughout the whole test, the participant was alone in the NEXT.ROOM, sitting on a chair in front of a desk positioned in the middle of the room (Figure 1), and following instructions provided through a computer screen. Once in the NEXT.ROOM (preliminary conditioned at 21 °C, neutral thermal condition [6]), the subject had the chance to read the participant information sheet and the test instructions, and provide the informed consent. Therefore, a sound calibration and an auditory test were performed to ensure that none of the participants was affected by auditory impairment, which may have affected the test results. During this phase, the participant had the chance to calibrate the headphones volume in order to adapt the incoming sound level as close as possible to a perceived real one (in this case we used the hands rubbing noise). Once the headphones calibration was completed, each subject took the audiogram test to assess a good hearing capacity after which the test began.

2.2.1. *Thermal and ventilation conditions variation*
Each experimental session comprises three phases: (i) a first phase at stationary and thermally neutral conditions, C0 (i.e. air temperature at 21 °C and MV at fan speed level L2), during which the subjects listened to and evaluated the environmental sound recordings, and finally expressed their judgement on thermal, visual, acoustic, and air quality perception through a 5-points Likert scale; (ii) 30-minutes

of rising air temperature (MV at fan speed level L4) during which the subject carried out the Big Five Personalities Traits test [26]; (iii) a third phase at stationary and thermally warmer conditions, C1 (i.e. air temperature at about 23 °C and MV at fan speed level L2), during which the subjects listened to and evaluated the same environmental sound recordings again and finally expressed again their judgement on thermal, visual, acoustic, and air quality perception through a 5-points Likert scale. The experimental procedure was the same for all the participants, which means that everyone experienced previously the thermally neutral condition and then the warmer one. The duration of the two phases under stationary thermal conditions (C0 and C1) was not a-priori set but was the time *taken* by each participant to fil the survey*;* it ranges between 60 *and* 90 minutes.

2.2.2. Environmental sound recordings

Each subject listened to and evaluated seven different environmental sound recordings comprising the following categories: beach (#1), woodlands (#2), quiet street (#3), pedestrian zone (#4), park (#5), shopping mall (#6), and busy street (#7). Soundscapes perception from the subjects' point of view (recorded during both the thermally neutral and warmer test phases) is here analysed by focusing on acoustic environments #2 and #7. These two environmental sound recordings were selected due to their evident contrast in terms of natural and artefact sounds (as #2 is characterised by nature-related features while #7 by traffic-related noises). The following eight soundscapes descriptors are considered in this study: pleasant, chaotic, vibrant, uneventful, calm, annoying, eventful, monotonous [27], [28].

3. Results and discussion

Physical environmental data were monitored only for 25 out of the 40 performed tests due to technical issues. Nevertheless, the analysis of collected survey responses presented in this section refers to all the 40 performed tests since the experimental set-up was always kept the same. So it is assumable that overall experienced conditions were always comparable to the monitored ones. The internal operative temperatures for the 25 tests with available environmental data were 21.6 °C ±0.8 °C at room conditions (C0) and 22.8 °C ±1.0 °C at room conditions (C1), with a temperature gap of 1.2 °C ±0.5 °C

Figure 3a shows obtained results in terms of the mean environmental comfort and sensation votes expressed by the 40 volunteers for all the investigated comfort domains at C0 (thermally neutral environment), and at C1 (thermally warmer environment). As expected, the greatest variation in terms of perceived comfort concerned the thermal domain, and the averaged thermal comfort vote decreased from +1.0 to +0.5. On the other hand, the observed changes in provided sensation votes are not consistent to the expectations. In fact, the averaged thermal sensation vote varied from 0.4 to 0.2 as the subject generally felt a slightly colder sensation at the end of the test despite the provided air temperature increase. It is worth noting that these variations are of a limited extent and refer to neutral and slightly warm sensation. This unexpected result could depend on two phenomena: (i) the metabolic decay, which is the progressive decrement of the internal heat production while sitting or generally performing sedentary activities, and (ii) subject acclimatisation. Indeed, the mean thermal sensation moves toward neutrality, so the experienced air temperature variation from the outdoor to the NEXT.ROOM may have impacted more than the provided temperature gap between C0 and C1 (Figure 4).

Figure 3b summarises the description of the cross-modal effect of thermal stimuli on acoustic perception. Recordings #2 (nature dominated) and #7 (traffic dominated) are analysed according to the collected responses on the eight soundscape descriptors at thermally neutral (C0) and thermally warm (C1) conditions. Overall, participants judged Recording #2 as more pleasant than Recording #7. They have also valued the #2 more calm and uneventful and yet more vibrant than the #7. Recording #7, on the other side, was perceived as always more chaotic and annoying than #2. The dominant soundscape descriptors of each track are still recognisable at the two different temperature conditions; however, the neat description assignment gets more neutral, from condition C0 to C1. This result may suggest that people cannot easily attribute different soundscape descriptors of the proposed sound recordings under less thermally comfortable conditions, with no specific distinction between nature or traffic dominated sound sources. Compared to Jin et al. [21] results, this more qualitative soundscape-based study showed that even slight thermal discomfort determines a significant attenuation in human soundscape perception. To double assess this effect, it would be useful repeating the same experiment with opposite thermal conditions exposure.

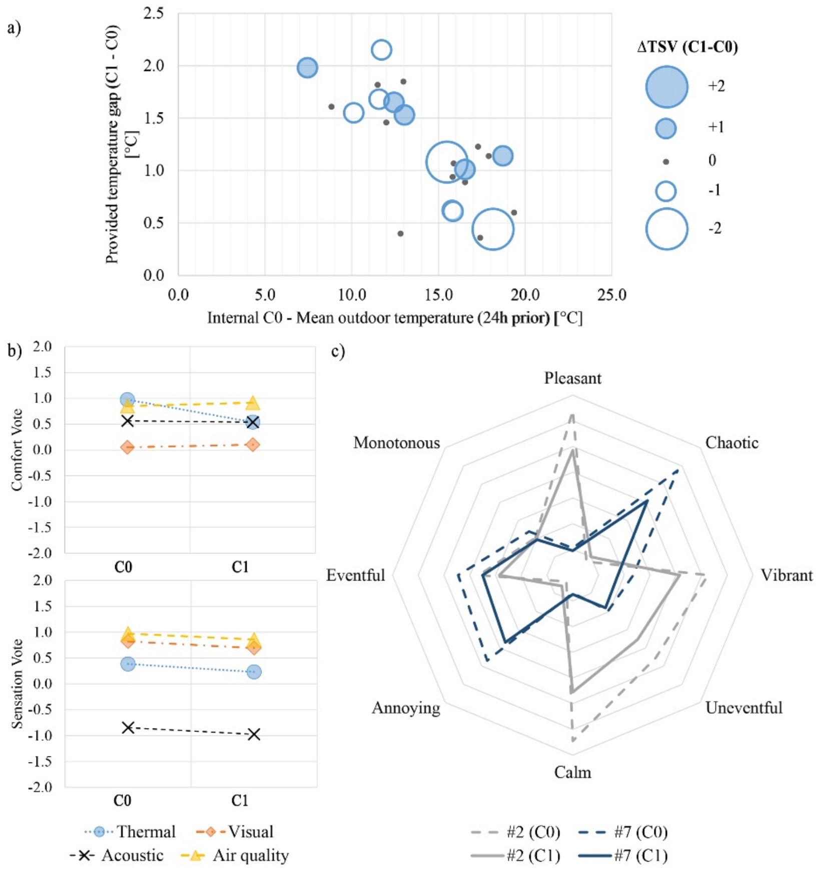


Figure 3. (a) the difference in between internal air temperature (C0) and the mean 24 hours prior outdoor temperature; (b)variation in expressed Thermal Comfort and Sensation Votes at the end of the first phase (C0) and third phase (C1); (c) acoustic environment records #2 and #7 main description according to subjects evaluation at the end of the first phase (C0) and third phase (C1)..

4. Conclusions

The presented experiment focused on the impact of thermal stimuli on environmental comfort and environmental acoustic perception. Observed variations in environmental comfort votes expressed at the end of the neutral and warmer conditions suggested that provided stimuli mostly impact the thermal domain. Furthermore, the average thermal sensation decreased from C0 to C1 (from slightly warm to neutral), suggesting the impact of the acclimatisation process that needs to be carefully considered in future experiments.

Concerning the cross-modal effect of thermal stimuli on the acoustic domain, results show that the dominant soundscapes descriptors of two recordings with neat sound features distinction are recognisable in both thermal environments; however, the neat description assignment gets more neutral from condition C0 to C1. This outcome may suggest that people are less able to assign different attributes of the proposed sound recordings under less thermally comfortable conditions. As future development of the research, the same experiment could be replicated while modifying the order of subjects' exposure to different thermal environments to counter-balance the possible influence of the exposure order. Moreover, these changes in the experimental protocol would allow to detect the effect of metabolic decay and better analyse the effect of presented environmental stimuli on perceived environmental sensations. Finally, the relationship between the personality description of the participants and their environmental perception will be pointed out as a further step of this research.

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